Research supported by the High Luminosity LHC project
HiLumi LHC: Correction of D2

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Outline

1. Introduction
2. Correction of $b_3$
3. Correction of $b_5$
4. Other Orders and Conclusions
Aim

- We want to use the non-linear correctors to correct the field quality of D2 (MBRD)
- This is an extension of the current correction algorithm
- Not trivial: D2 has two apertures, correctors have one
  ⇒ Correction of both beams simultaneously!
Setup

- DA is calculated over:
  - 5 angles (15°, 30°, 45°, 60°, and 75°)
  - 60 random realisations (‘seeds’)
- Unless otherwise noted, all errors assigned at nominal value
- HLLHC 1.0 optics
Example DA plot

- **Absolute maximum**
  - (maximum angle over all seeds)

- **Individual seed lines**
  - (average over angles per seed)

- **Average DA**
  - (average over angles and over seeds)

- **Absolute minimum**
  - (minimum angle over all seeds)
Approach

- Best we can do, is to correct the average of the errors of both apertures in D2
- Systematic errors in D2 are antisymmetric for even and symmetric for odd orders, and skew error components have no systematic part
  - Systematic errors: only $b_3$ and $b_5$ can be corrected
  - Random error parts can be corrected at all orders (up to $b_6$), but physical reproductivity should be taken with a grain of salt
- Closest single-aperture magnet is D1
  - use it to compare efficiency of correction algorithm
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DA in function of $b_3$ of D1

Beam 1 (no errors in D2)  Beam 4

$E = 7000 \text{ GeV}$
$\varepsilon_n = 3.75 \mu m$
$\beta_{1^*} = 0.15 \text{ m}$
$\beta_{2^*} = 10 \text{ m}$
$\beta_{5^*} = 0.15 \text{ m}$
$\beta_8^* = 3 \text{ m}$
$\theta_{c,1,5}^* = 590 \text{ mrad}$
$d_{sep}^{1,5} = 4 \text{ mm}$
$Q_x = 62.31$
$Q_y = 60.32$
$Q' = 3$
$I_{MO} = 0 \text{ A}$
$\mu_{1\rightarrow 5}^x = 31.210$
$\mu_{1\rightarrow 5}^y = 30.373$
$\phi_1 = 90^\circ$
$\phi_5 = 0^\circ$

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-- no correction
--- full correction

nominal
DA in function of $b_3$ of D2

Beam 1

Beam 4

$E = 7000 \text{ GeV}$

$\varepsilon_n = 3.75 \mu m$

$\beta_1^* = 0.15 \text{ m}$

$\beta_2^* = 10 \text{ m}$

$\beta_5^* = 0.15 \text{ m}$

$\beta_8^* = 3 \text{ m}$

$\theta_{c,5}^{1,5} = 590 \text{ mrad}$

$d_{sep} = 4 \text{ mm}$

$Q_x = 62.31$

$Q_y = 60.32$

$Q' = 3$

$I_{MO} = 0 \text{ A}$

$\mu_{x}^{1\rightarrow 5} = 31.210$

$\mu_{y}^{1\rightarrow 5} = 30.373$

$\phi_1 = 90^\circ$

$\phi_5 = 0^\circ$
Correction of $b_3$ of D2

- Correction algorithm for $b_3$ of D2 works efficiently
- Especially for higher values of $b_3$
Summary of $b_3$ correction for D1 and D2

- **D1:** $b_3=0$ (no correction)
  - D2: No errors
- **D1:** $b_3=-0.9$ (full correction)
  - D2: $b_3=3.8$ (no correction)
- **D1:** $b_3=-3.5$ (full correction)
  - D2: $b_3=3.8$ (no correction)

- **D1:** $b_3=-0.9$ (no correction)
  - D2: No errors
- **D1:** $b_3=-0.9$ (full correction)
  - D2: $b_3=3.8$ (full correction)
- **D1:** $b_3=-3.5$ (full correction)
  - D2: $b_3=3.8$ (full correction)

- **D1:** $b_3=-0.9$ (full correction)
  - D2: No errors
- **D1:** $b_3=-0.9$ (full correction)
  - D2: $b_3=9.9$ (full correction)
Strength of $b_3$ correctors for D1 (beam 1)
Strength of $b_3$ correctors for D1 (beam 4)
Strength of $b_3$ correctors for D2 (beam 1)
Strength of $b_3$ correctors for D2 (beam 4)
Outline

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DA in function of $b_5$ of D1

Beam 1  (no errors in D2)  Beam 4

$E = 7000 \text{ GeV}$
$\varepsilon_n = 3.75 \mu\text{m}$
$\beta^*_{1} = 0.15 \text{ m}$
$\beta^*_{2} = 10 \text{ m}$
$\beta^*_{5} = 0.15 \text{ m}$
$\beta^*_{8} = 3 \text{ m}$
$\theta_{c1,5} = 590 \text{ mrad}$
$d_{sep} = 4 \text{ mm}$
$Q_x = 62.31$
$Q_y = 60.32$
$Q' = 3$
$I_{\text{MO}} = 0 \text{ A}$
$\mu_{1\rightarrow5} = 31.210$
$\mu_{1\rightarrow5} = 30.373$
$\phi_1 = 90^\circ$
$\phi_5 = 0^\circ$

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DA in function of $b_5$ of D2

**Beam 1**

- $E = 7000$ GeV
- $\varepsilon_n = 3.75 \, \mu\text{m}$
- $\beta_1^* = 0.15 \, \text{m}$
- $\beta_2^* = 10 \, \text{m}$
- $\beta_5^* = 0.15 \, \text{m}$
- $\beta_8^* = 3 \, \text{m}$
- $\theta_1^{1,5} = 590 \, \text{mrad}$
- $d_{sep}^{1,5} = 4 \, \text{mm}$
- $Q_x = 62.31$
- $Q_y = 60.32$
- $Q' = 3$
- $I_{MO} = 0 \, \text{A}$
- $\mu_{x}^{1\rightarrow5} = 31.210$
- $\mu_{y}^{1\rightarrow5} = 30.373$
- $\phi_1 = 90^\circ$
- $\phi_5 = 0^\circ$

**Beam 4**

- $E = 7000$ GeV
- $\varepsilon_n = 3.75 \, \mu\text{m}$
- $\beta_1^* = 0.15 \, \text{m}$
- $\beta_2^* = 10 \, \text{m}$
- $\beta_5^* = 0.15 \, \text{m}$
- $\beta_8^* = 3 \, \text{m}$
- $\theta_1^{1,5} = 590 \, \text{mrad}$
- $d_{sep}^{1,5} = 4 \, \text{mm}$
- $Q_x = 62.31$
- $Q_y = 60.32$
- $Q' = 3$
- $I_{MO} = 0 \, \text{A}$
- $\mu_{x}^{1\rightarrow5} = 31.210$
- $\mu_{y}^{1\rightarrow5} = 30.373$
- $\phi_1 = 90^\circ$
- $\phi_5 = 0^\circ$

- **no correction**
- **full correction**

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Non-Linear Correction
Correction of $b_5$

- Correction algorithm for $b_5$ works efficiently in the case of D1 (dependence on $b_5$ becomes horizontal line)
- But not really for D2!
- Let’s expand the region in $b_5$ to investigate the trend
DA in function of $b_5$ of D1

Beam 1  
(no errors in D2)  
Beam 4

$E = 7000 \text{ GeV}$
$\varepsilon_n = 3.75 \mu m$
$\beta_1^* = 0.15 \text{ m}$
$\beta_2^* = 10 \text{ m}$
$\beta_5^* = 0.15 \text{ m}$
$\beta_S^* = 3 \text{ m}$
$\theta_{c,15} = 590 \text{ mrad}$
$d_{sep} = 4 \text{ mm}$
$Q_x = 62.31$
$Q_y = 60.32$
$Q' = 3$
$I_{MO} = 0 \text{ A}$
$\mu_1^{x\rightarrow5} = 31.210$
$\mu_y^{x\rightarrow5} = 30.373$
$\phi_1 = 90^\circ$
$\phi_5 = 0^\circ$

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Non-Linear Correction 21
DA in function of $b_5$ of D2

Beam 1

Beam 4

$E = 7000$ GeV
$\varepsilon_n = 3.75 \, \mu m$
$\beta_1^* = 0.15 \, m$
$\beta_2^* = 10 \, m$
$\beta_5^* = 0.15 \, m$
$\beta_8^* = 3 \, m$
$\theta_{c1,5} = 590 \, \text{mrad}$
$d_{sep}^{1,5} = 4 \, \text{mm}$
$Q_x = 62.31$
$Q_y = 60.32$
$Q' = 3$
$I_{MO} = 0 \, \text{A}$
$\mu_{1\rightarrow5}^x = 31.210$
$\mu_{1\rightarrow5}^y = 30.373$
$\phi_1 = 90^\circ$
$\phi_5 = 0^\circ$

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no correction
green full correction
Correction of $b_5$

- Correction algorithm for $b_5$ still works in the case of D1, but less efficient (errors are not fully corrected, but there is still a gain)
- Correction has a minimal effect for the nominal value of $b_5$ in D2, but lowers dynamic aperture for higher values
  \[ \Rightarrow \text{Correction seems faulty!} \]
- Let’s have a look at the resonance driving terms to see if the correction algorithm minimises these
  \[ \Rightarrow \text{Compare } b_3 \text{ with } b_5 \]
Resonance driving terms: $b_3$ (beam 1)

Resonance $\{2, 1\}$

Resonance $\{1, 2\}$

- No D2, no correctors
- No D2, with correctors
- With D2, no correctors
- With D2, with correctors

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Resonance driving terms: $b_3$  (beam 1)

Resonance  \{3, 0\}  

Resonance  \{0, 3\}  

- No D2, no correctors
- No D2, with correctors
- With D2, no correctors
- With D2, with correctors
Resonance driving terms: $b_5$ (beam 1)

Resonance $\{5, 0\}$

Resonance $\{0, 5\}$

- No D2, no correctors
- No D2, with correctors
- With D2, no correctors
- With D2, with correctors

Systematic $b_5$ of D2
Resonance driving terms: $b_5$ (beam 1)

Resonance $\{3, 2\}$

Resonance $\{2, 3\}$
Resonance driving terms: $b_5$ (beam 1)

Resonance \{4, 1\}

Resonance \{1, 4\}

- No D2, no correctors
- No D2, with correctors
- With D2, no correctors
- With D2, with correctors
Correlation of Driving Terms and DA

Resonance: \{(5, 0)\}  \[ b_5 \text{ of D2: } -35 \quad \text{IP: 1} \]
Correlation of Driving Terms and DA

Resonance: \(3, 0\)  
\(b_3\) of D2: \(-4\)  
IP: 1

Minimum DA

Driving Term
Conclusion

- There is no difference in the minimisation between $b_3$ and $b_5$
- Correlation between driving terms and dynamic aperture is unclear (but should be present)
  - Also not visible for $b_3$
  - Variation is not big enough
- Need to study the correlation deeper by increasing the random part until the correlation becomes apparent
  - Other resonance might correlate better with DA!
Other orders of D2

- Concerning the systematic part of the errors, only $b_3$ and $b_5$ can be corrected.
- But for the random parts, all orders can be corrected (still by taking the average over both beams).
- This might be overly optimistic and no reproducible in reality.

⇒ However, effect is expected to be negligible
⇒ Investigate the impact on DA of correcting other orders.
Other orders of D2 (beam 1)

$E = 7000 \text{ GeV}$

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$\beta_{1}^{*} = 0.15 \text{ m}$

$\beta_{2}^{*} = 10 \text{ m}$

$\beta_{5}^{*} = 0.15 \text{ m}$

$\beta_{8}^{*} = 3 \text{ m}$

$\theta_{c,5}^{1.5} = 590 \text{ mrad}$

$d_{sep}^{1.5} = 4 \text{ mm}$

$Q_{x} = 62.31$

$Q_{y} = 60.32$

$Q' = 3$

$I_{MO} = 0 \text{ A}$

$\mu_{1\rightarrow 5}^{1} = 31.210$

$\mu_{1\rightarrow 5}^{y} = 30.373$

$\phi_{1} = 90^\circ$

$\phi_{5} = 0^\circ$
$E = 7000 \text{ GeV}$

$\varepsilon_n = 3.75 \, \mu m$

$\beta_1^* = 0.15 \, \text{m}$

$\beta_2^* = 10 \, \text{m}$

$\beta_3^* = 0.15 \, \text{m}$

$\beta_8^* = 3 \, \text{m}$

$\theta_{c,5}^1 = 590 \, \text{mrad}$

$d_{sep}^{1,5} = 4 \, \text{mm}$

$Q_x = 62.31$

$Q_y = 60.32$

$Q' = 3$

$I_{MO} = 0 \, \text{A}$

$\mu_{x \rightarrow 5}^1 = 31.210$

$\mu_{y \rightarrow 5}^1 = 30.373$

$\phi_1 = 90^\circ$

$\phi_5 = 0^\circ$
Final Conclusions

- Correction of $b_3$ works very well
- Correction of $b_5$ is a bit less reliable; maybe other choice of resonance minimisation improves the situation
- Correction of other orders has no effect (as expected)